Measuring $\psi'' \to \rho\pi$ in e^+e^- experiment

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In S- and D-wave mixing scheme, the branching ratio of $\psi'' \to \rho\pi$ is estimated. Together with the continuum cross section of $\rho\pi$ estimated by form factor, the observed cross section of $\rho\pi$ production at ψ'' in e^+e^- experiment is calculated taking into account the interference effect between the resonance and continuum amplitudes and the initial state radiative correction. The behavior of the cross section reveals that the disappearance of $\rho\pi$ signal just indicates the existence of the corresponding branching ratio $\mathcal{B}_{\psi'' \to \rho\pi}$ at the order of 10^{-4}.

1. Introduction

The lowest charmonium resonance above the charmed particle production threshold is $\psi(3770)$ (shorted as ψ'') which provides a rich source of $D^0\overline{D^0}$ and D^+D^- pairs, as anticipated theoretically [1]. However, non-$D\overline{D}$ (*non-charmed final state*) decay of ψ'' was studied theoretically and searched experimentally almost two decades ago. The OZI violation mechanism [2] was utilized to understand the possibility of non-$D\overline{D}$ decay of ψ'' [3], and experimental investigations involving noncharmed decay modes could be found in Ref. [4].

To explain the large Γ_{ee} of ψ'', it is suggested [5,6] that the mass eigenstates $\psi(3686)$ (shorted as ψ') and ψ'' are the mixtures of the S- and D-wave of chamonia, namely $\psi(2^3S_1)$ state and $\psi(1^3D_1)$ state. Recently it is proposed that such mixing gives possible solution to the so-called "$\rho\pi$ puzzle" in ψ' and J/ψ decays [7]. In this scheme

$$\begin{aligned} \langle\rho\pi|\psi'\rangle &= \langle\rho\pi|2^3S_1\rangle\cos\theta - \langle\rho\pi|1^3D_1\rangle\sin\theta , \\ \langle\rho\pi|\psi''\rangle &= \langle\rho\pi|2^3S_1\rangle\sin\theta + \langle\rho\pi|1^3D_1\rangle\cos\theta , \end{aligned} \quad (1)$$

where θ is the mixing angle between pure $\psi(2^3S_1)$ and $\psi(1^3D_1)$ states and is fitted from the leptonic widths of ψ'' and ψ' to be either $(-27\pm2)°$ or $(12 \pm 2)°$ [7]. The latter value of θ is consistent with the coupled channel estimates [5,8]

and with the ratio of ψ' and ψ'' partial widths to $J/\psi\pi^+\pi^-$ [6,9]. Hereafter, the discussions in this Letter are solely for the mixing angle $\theta = 12°$.

If the mixing and coupling of ψ' and ψ'' lead to complete cancellation of $\psi' \to \rho\pi$ decay ($\langle\rho\pi|\psi'\rangle = 0$), the missing $\rho\pi$ decay mode of ψ' shows up instead as decay mode of ψ'', enhanced by the factor $1/\sin^2\theta$. For $\theta = 12°$, the ψ'' decay branching ratio [7]

$$\mathcal{B}_{\psi''\to\rho\pi} = (4.1 \pm 1.4) \times 10^{-4} . \quad (2)$$

With the resonance parameters of ψ'' from PDG2002 [10], the total resonance cross section of ψ'' production at Born order is

$$\sigma_{\psi''}^{Born} = \frac{12\pi}{M_{\psi''}^2} \cdot \mathcal{B}_{ee} = (11.6 \pm 1.8) \text{ nb} .$$

Here $M_{\psi''}$ and $\mathcal{B}_{ee}$ are the mass and e^+e^- branching ratio of ψ''. With Eq. (2), the Born order cross section of $\psi'' \to \rho\pi$ is

$$\sigma_{\psi''\to\rho\pi}^{Born} = (4.8 \pm 1.9) \text{ pb} .$$

It is known that at $\sqrt{s} = M_{\psi''}$, the total continum cross section, which is 13 nb, is larger than that of resonance. Due to the OZI suppression, the total cross section of non-$D\overline{D}$ decay from the resonance is much smaller than that from the continuum. For an individual exclusive mode, the contribution from the continuum process may be larger than or comparable with that from the resonance decay. For the $\rho\pi$ mode, the cross section

of the resonance decay is more than three orders of magnitude smaller than the total continuum cross section, thus the contribution from the continuum and the corresponding interference effect must be studied carefully and taken into account in case of significant modification of the experimentally observed cross section.

In the following sections, the Born order cross sections from the continuum and the resonance decays are given by virtue of the form factor and the S- and D-wave mixing model, then the experimental observable is calculated taking into account the radiative correction and experimental conditions. Finally the dependence of the observed $\rho\pi$ cross section on the phase between the OZI suppressed strong decay amplitude and the electromagnetic decay amplitude is discussed.

2. Born order cross section of $\rho\pi$

In e^+e^- annihilation experiment at the charmonium resonance ψ'', there are three amplitudes responsible for $\rho^0\pi^0$ final state[2]: the continuum one-photon annihilation amplitude a_c, the electromagnetic decay amplitude of the resonance a_γ and the OZI suppressed strong decay amplitude of the resonance a_{3g} [11]:

$$A_{\rho^0\pi^0}(s) = a_{3g}(s) + a_\gamma(s) + a_c(s) \ .$$

As to electromagnetic interaction, the a_c and a_γ are related to the $\rho\pi$ form factor:

$$a_c(s) = \mathcal{F}_{\rho^0\pi^0}(s) \ ,$$

and

$$a_\gamma(s) = B(s) \cdot \mathcal{F}_{\rho^0\pi^0}(s) \ ,$$

with the notation

$$B(s) \equiv \frac{3\sqrt{s}\Gamma_{ee}/\alpha}{s - M_{\psi''}^2 + iM_{\psi''}\Gamma_t} \ ,$$

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[2]Generally for certain final state f, three amplitudes describe the following three processes:

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\begin{aligned}
a_{3g} : & \quad e^+e^- \to \psi', \psi'' \to ggg \to f \ ; \\
a_\gamma : & \quad e^+e^- \to \psi', \psi'' \to \gamma^* \to f \ ; \\
a_c : & \quad e^+e^- \to \gamma^* \to f \ .
\end{aligned}
$$

The first two processes are called resonance processes, and are denoted together as $\psi', \psi'' \to f$ for short, while the third one is called continuum process and denoted as $e^+e^- \to f$ for short.

where α is the QED fine structure constant, Γ_t and Γ_{ee} are the total width and e^+e^- partial width of ψ''. The strong decay amplitude can be parametrized in terms of its relative phase (ϕ) and relative strength ($\mathcal{C}$) to the electromagnetic decay amplitude:

$$a_{3g}(s) = \mathcal{C}e^{i\phi}a_\gamma(s) \ ,$$

where $\mathcal{C}$ is taken to be real.

Using $\mathcal{C}$, ϕ and $\mathcal{F}_{\rho^0\pi^0}$, $A_{\rho^0\pi^0}$ becomes [12]

$$A_{\rho^0\pi^0}(s) = [(\mathcal{C}e^{i\phi} + 1)B(s) + 1] \cdot \mathcal{F}_{\rho^0\pi^0}(s) \ , \quad (3)$$

so the total $\rho^0\pi^0$ cross section at Born order is

$$\sigma_{\rho^0\pi^0}^{Born}(s) = \frac{4\pi\alpha^2}{3s^{3/2}}|A_{\rho^0\pi^0}(s)|^2 q_{\rho^0\pi^0}^3 \ , \quad (4)$$

where $q_{\rho^0\pi^0}$ is the three momentum of ρ^0 or π^0 in the final state.

Since there is no experimental information on $\rho\pi$ cross section for the continuum process at resonance peak, the $\omega\pi^0$ form factor is used for estimation. According to the SU(3) symmetry [13],

$$\mathcal{F}_{\rho^0\pi^0}(s) = \frac{1}{3}\mathcal{F}_{\omega\pi^0}(s) \ . \quad (5)$$

$\mathcal{F}_{\omega\pi^0}$ is obtained via [14]

$$\left|\frac{\mathcal{F}_{\omega\pi^0}(s)}{\mathcal{F}_{\omega\pi^0}(0)}\right| = \frac{(2\pi f_\pi)^2}{3s} \ ,$$

where f_π is the pion decay constant. Using the $\omega\pi^0$ form factor at $Q^2 = 0$ from the crossed channel decay $\omega \to \gamma\pi^0$,

$$|\mathcal{F}_{\omega\pi^0}(s)| = \frac{0.531 \text{ GeV}}{s} \ ,$$

which is in good agreement with the experimental result at $\sqrt{s} = M_{\psi'}$ [15].

With above form factor, the Born order continuum cross section of $\rho\pi$ production at ψ'' resonance peak is [3]

$$\sigma_{e^+e^- \to \rho\pi}^{Born} = 4.4 \text{ pb} \ .$$

For the resonance part,

$$|(\mathcal{C}e^{i\phi}+1)\cdot \mathcal{F}_{\rho^0\pi^0}(M_{\psi''}^2)|^2 \Gamma_{ee}^0 M_{\psi''}^2 = |\langle\rho^0\pi^0|\psi''\rangle|^2 \ , (6)$$

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[3]Hereafter $\rho^0\pi^0$ is used for one of the three different $\rho\pi$ isospin states, and $\rho\pi$ for the sum of them.

where Γ_{ee}^0 is the e^+e^- partial width without vacuum polarization correction [16]. Starting from Eq. (1), it can be acquired

$$\langle\rho^0\pi^0|\psi''\rangle = \frac{\langle\rho^0\pi^0|2^3S_1\rangle}{\sin\theta} - \langle\rho^0\pi^0|\psi'\rangle\tan\theta .$$

Since there could be an unknown phase between $\langle\rho^0\pi^0|2^3S_1\rangle$ and $\langle\rho^0\pi^0|1^3D_1\rangle$, or equivalently a phase (denoted as α) between $\langle\rho^0\pi^0|2^3S_1\rangle$ and $\langle\rho^0\pi^0|\psi'\rangle$, $|\langle\rho^0\pi^0|\psi''\rangle|$ is constrained in a range. With model-dependent estimation $\mathcal{B}_{\psi'\to\rho\pi} = (1.11 \pm 0.87) \times 10^{-4}$ [12], and $\langle\rho^0\pi^0|2^3S_1\rangle$ in Ref. [7], for $\theta = 12°$,

$$|\langle\rho^0\pi^0|\psi''\rangle|^2 = (1.8 \sim 5.2) \times 10^{-5} \text{ GeV} ,$$

or equivalently

$$\mathcal{B}_{\psi''\to\rho\pi} = (2.5 \sim 7.2) \times 10^{-4} \quad , \tag{7}$$

which corresponds to the variation of α from $0°$ to $180°$. So the relation between $\mathcal{C}$ and ϕ could derived from Eq. (6).

For a given $\mathcal{B}_{\psi''\to\rho\pi}$, according to Eqs. (3) and (4), the observed cross section depends on the interference pattern between the continuum one-photon amplitude and the ψ'' decay amplitude. In case of $\phi = \pm 90°$, the maximum constructive or destructive interference between a_{3g} and a_c happens at the resonance peak; while $\phi = 0°$ or $180°$ leads to constructive or destructive interference between a_{3g} and a_γ.

3. Observed cross section of $\rho\pi$

Due to the rapidly varying Breit-Wigner formula and the $\rho\pi$ form factor as the center of mass energy changes, the observed cross section depends strongly on the initial state radiative correction which reduces the center of mass energy, and the invariant mass cut (m_{cut}) which removes the events produced by the initial state radiation. Taking these into account, the observed cross section becomes

$$\sigma^{obs}(s) = \int_0^{x_m} dx F(x,s)\frac{\sigma^{Born}(s(1-x))}{|1 - \Pi(s(1-x))|^2} ,$$

where

$$x_m = 1 - m_{cut}^2/s .$$

$F(x,s)$ has been calculated to the accuracy of 0.1% [17–19] and $\Pi(s)$ is the vacuum polarization factor [20].

It should be emphasized that the radiative correction modifies the Born order cross section in a profound way. Firstly, it shifts upward the maximum total cross section [21] to the energy $M_{\psi''} + 0.75$ MeV[4]. Secondly, the radiative correction changes the Born order cross section significantly. For example, if $\phi = -90°$ and $\mathcal{B}_{\psi''\to\rho\pi} = 4.1 \times 10^{-4}$, $\sigma_{\rho\pi}^{Born} = 5.6 \times 10^{-3}$ pb, after radiative correction $\sigma_{\rho\pi}^{obs} = 0.31$ pb for $x_m = 0.02$.

The dependence of the observed cross section on the invariant mass cut is illustrated in Fig. 1, for the branching ratio in Eq. (7) and $\phi = -90°$. It is obvious that a tighter invariant mass cut results in a smaller observed cross section. In the following analysis, $x_m = 0.02$ is taken, which means a cut of $\rho\pi$ invariant mass within 38 MeV from $M_{\psi''}$, or, near the midway between ψ' and ψ'' masses.
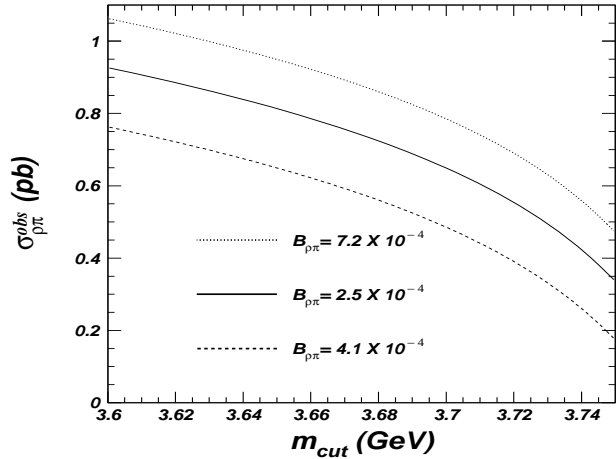

Figure 1. The observed $\rho\pi$ cross section as a function of m_{cut} for three branching ratios ($\phi = -90°$).

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[4]In this Letter, it is assumed that the experiments take data at the energy which yields the maximum total cross section. The observed cross sections are calculated at this energy instead of the nominal resonance mass.

It is worthy to notice the variation of the observed $\rho\pi$ cross section with the phase α between $\langle\rho\pi|2^3S_1\rangle$ and $\langle\rho\pi|\psi'\rangle$. When α varies from $0°$ to $180°$, $\sigma_{\rho\pi}^{obs}$ in Fig. 1 moves from the line for $\mathcal{B}_{\psi''\to\rho\pi} = 2.5 \times 10^{-4}$ to that for $\mathcal{B}_{\psi''\to\rho\pi} = 4.1 \times 10^{-4}$, and then increases to that for $\mathcal{B}_{\psi''\to\rho\pi} = 7.2 \times 10^{-4}$, at a specific invariant mass cut.

The phase ϕ between a_{3g} and a_γ has significant effect on the observed cross section due to different interference patterns. Fig. 2(a) shows the observed cross sections at ψ'' resonance peak as functions of $\mathcal{B}_{\psi''\to\rho\pi}$ with $x_m = 0.02$ and $\phi = -90°$, $90°$, $0°$ and $180°$, respectively. For the destructive interference between a_{3g} and a_c ($\phi = -90°$), the cross section reaches its minimum for $\mathcal{B}_{\psi''\to\rho\pi} \approx 4.1\times10^{-4}$, which corresponds to the resonance cross section of 3.3 pb, but $\sigma_{\rho\pi}^{obs}$ is only 0.31 pb, an order of magnitude smaller.

Above calculations of the observed cross section could be extended to other 1^-0^- decay modes, such as $K^{*0}\overline{K^0} + c.c.$ and $K^{*+}K^- + c.c.$, whose amplitudes are expressed as [12]:

$$A_{K^{*0}\overline{K^0}} = [(\mathcal{C}\mathcal{R}e^{i\phi} - 2)B(s) - 2]\mathcal{F}_{\rho^0\pi^0}(s) , \quad (8)$$

$$A_{K^{*+}K^-} = [(\mathcal{C}\mathcal{R}e^{i\phi} + 1)B(s) + 1]\mathcal{F}_{\rho^0\pi^0}(s) , \quad (9)$$

where $\mathcal{R} \equiv (a_{3g} + \epsilon)/a_{3g}$, with ϵ describing the SU(3) breaking effect. It is assumed that ϵ has the same phase as a_{3g} [22], so $\mathcal{R}$ is real. Using $\mathcal{C}$ determined from $\mathcal{B}_{\psi''\to\rho\pi}$ and $\mathcal{R} = 0.775$ from fitting $J/\psi \to 1^-0^-$ decay [12], the cross section of $K^{*0}\overline{K^0}$ or $K^{*+}K^-$ is calculated by Eq. (4) merely with the substitution of $A_{K^{*0}\overline{K^0}}$ or $A_{K^{*+}K^-}$ for $A_{\rho^0\pi^0}$. Their observed cross sections at ψ'' resonance peak as functions of $\mathcal{B}_{\psi''\to\rho\pi}$ are shown in Fig. 2(b) for $\phi = -90°$ and $x_m = 0.02$. It could be seen that the cross section of $K^{*0}\overline{K^0} + c.c.$ is much larger than those of $\rho\pi$ and $K^{*+}K^- + c.c.$ in a wide range of the $\rho\pi$ branching ratio.

Since the data at ψ'' resonance peak alone can not fix all parameters ($\mathcal{C}$, ϕ, and $\mathcal{F}_{\rho\pi}$) in $\mathcal{B}_{\psi''\to\rho\pi}$ determination, the correct way of measuring the branching ratio is through energy scan of resonance. Fig. 3 shows the observed $\rho\pi$ cross section in the vicinity of the ψ'' resonance, with $x_m = 0.02$ and the branching ratio in Eq. (7) for four values of ϕ: $-90°$, $+90°$, $0°$, and $180°$. The
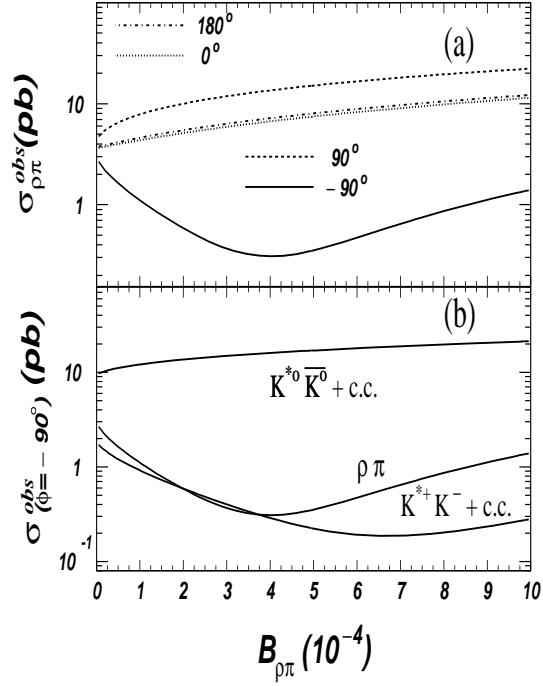

Figure 2. (a) Observed $\rho\pi$ cross section as a function of $\mathcal{B}_{\psi''\to\rho\pi}$ for different phases, and (b) observed cross sections of $K^{*0}\overline{K^0} + c.c.$, $K^{*+}K^- + c.c.$, and $\rho\pi$ as functions of $\mathcal{B}_{\psi''\to\rho\pi}$.

hatched areas are due to the variation of α. For $\phi = 0°$ or $180°$, the maximum observed cross section is above or below the resonance mass. Only for $\phi = +90°$ the maximum observed cross section is near the resonance peak. Here the most interesting phenomenon is, with $\phi = -90°$, the observed cross section reaches its minimum near the resonance peak! This phenomenon suggests that at the resonance peak the undetectable experiment cross section of $\rho\pi$ just indicates the existence of the corresponding branching ratio at the order of 10^{-4}.

4. Discussion

As shown in Fig. 3, the line shape of the $\rho\pi$ cross section is sensitive to the phase ϕ. If the fine scan is infeasible, at least at three energy
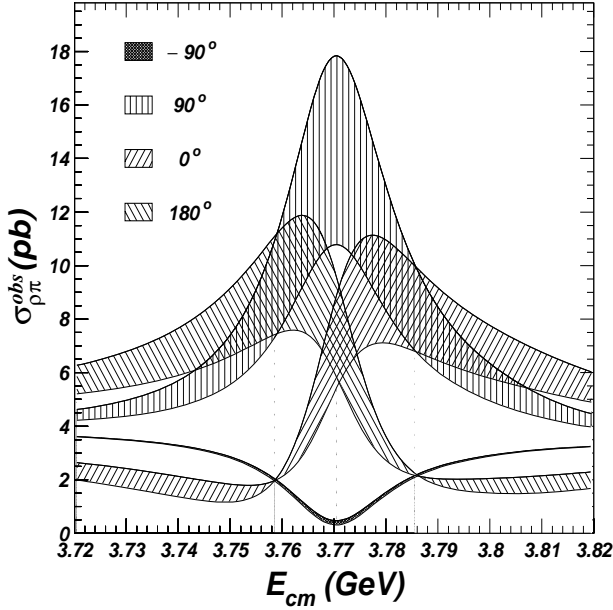
Figure 3. Observed $\rho\pi$ cross section varies with the center of mass energy for different phases: $\phi = -90°$, $+90°$, $0°$, and $180°$, respectively.

points the data must be taken in order to fix the three parameters in Eq. (3): $\mathcal{C}$, ϕ and $\mathcal{F}_{\rho^0\pi^0}$. According to Eq. (1), with $\rho\pi$ branching ratios at ψ' and ψ'', and the magnitude of $\langle\rho\pi|2^3S_1\rangle$, which is derived in Ref. [7], the relative phase α could also be determined. If only the data at ψ'' peak is available, a model-dependent way to determine the $\rho\pi$ branching ratio is to look for more 1^-0^- modes, such as $K^{*0}\overline{K^0} + c.c.$, $K^{*+}K^- + c.c.$ and $\omega\pi^0$. Notice in Eqs. (3), (5), (8) and (9), the three modes are parametrized by four parameters: $\mathcal{C}$, $\mathcal{R}$, ϕ and $\mathcal{F}_{\omega\pi^0}$. With the measurement of $\mathcal{F}_{\omega\pi^0}$ through $\omega\pi^0$ mode, the other three parameters could be solved from Eqs. (3), (8) and (9).

Eqs. (3) and (8) indicate opposite interference patterns between a_{3g} and a_c for $\rho^0\pi^0$ and $K^{*0}\overline{K^0}$. That is, if the interference between a_{3g} and a_c for $\rho\pi$ is **destructive**, then such interference is just **constructive** for $K^{*0}\overline{K^0}$+c.c. and *vice versa*. In the resonance scan, if $\sigma_{\rho\pi}^{obs}$ reaches its valley near

ψ'' resonant mass, $\sigma_{K^{*0}\overline{K^0}+c.c.}^{obs}$ reaches its peak[5]. This means if the observed $\rho\pi$ cross section at ψ'' is smaller than that at continuum, the observed $K^{*0}\overline{K^0}$+c.c. cross section at ψ'' will be larger. So the measurements of $K^{*0}\overline{K^0}$+c.c. and $\rho\pi$ provide a crucial test of the interference pattern between a_{3g} and a_c.

There are theoretical arguments in favor of the orthogonality between a_{3g} and a_γ [23] of the charmonium decays. The phenomenological analyses for many two-body decay modes: 1^-0^-, 0^-0^-, 1^-1^-, 1^+0^-, and Nucleon anti-Nucleon on J/ψ data support this assumption [22,24]. The recent analysis of $\psi' \to 1^-0^-$ decays which took into account the contribution from the continuum, found that the phase $\phi = -90°$ could fit current available data within experimental uncertainties and $\phi = +90°$ could be ruled out [12]. Similar analysis of $\psi' \to 0^-0^-$ decays also favors the orthogonal phase [25]. For ψ'' , it is of great interest here to note the search of $\rho\pi$ mode by MARK-III [4] at the ψ'' peak. The result corresponds to the upper limit of the $\rho\pi$ production cross section of 6.3 pb at 90% C. L., which favors $\phi = -90°$ than other possibilities as seen from Fig. 3. These experimental information suggests the phase $\phi = -90°$ between a_{3g} and a_γ be universal for all quarkonia decays.

At last, a few words about the effect of the beam energy spread Δ for cross section measurement [15]. ψ'' is a relatively wide resonance, for a collider with small energy spread, such as $\Delta = 1.4$ MeV at BES/BEPC [26], this effect is negligible. With increasing Δ, the correction becomes larger. For example, on a collider with $\Delta = 5$ MeV, for $\phi = -90°$ and $x_m = 0.02$, the observed cross section of $\rho\pi$ for $\mathcal{B}_{\psi''\to\rho\pi} = 4.1\times10^{-4}$ is more than doubled to 0.68 pb comparing with the value without energy spread effect.

5. Summary

By virtue of S- and D-wave mixing model, $\mathcal{B}_{\psi''\to\rho\pi}$ is estimated, together with the estimated

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[5]In Fig. 3, if the scan behavior of $\sigma_{\rho\pi}^{obs}$ is similar to the curve corresponding to $\phi = -90°$, $\sigma_{K^{*0}\overline{K^0}+c.c.}^{obs}$ would be similar to the $\rho\pi$ curve corresponding to $\phi = +90°$.

$\sigma_{e^+e^-\to\rho\pi}$ by form factor, the observed $\rho\pi$ cross section at ψ'' in e^+e^- experiment, which takes into account the initial state radiative correction, has been calculated. The study shows that the disappearance of $\rho\pi$ cross section at ψ'' peak just indicates the branching ratio of $\psi'' \to \rho\pi$ at the order of 10^{-4}.

Besides the information of ψ'', if the phase analyses of J/ψ and ψ' are also taken into consideration, it is natural to conclude that the phase $\phi = -90°$ between a_{3g} and a_γ is universal for all quarkonia decays.

In the forthcoming high luminosity experiments of ψ'' at CLEO-c [27] and BES-III [28], the property of $\rho\pi$ decay and the feature of the phase are expected to be tested quantitatively.

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